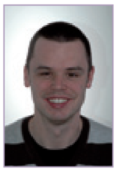
Infrared welding of carbon fabric reinforced thermoplastics

The wide acceptance of high-performance composite materials introduces an issue regarding the bonding of these reinforced polymer materials. This study assesses the use of the infrared welding method for a carbon fabric with a thermoplastic resin system.

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For better resistance to static and dynamic loads on a composite structure during its life span, reinforced thermoplastic parts are increasingly being used to replace metallic or thermosetting composite parts. Therefore, the joining of thermoplastic composite parts during the manufacturing and assembly process for such structures has become an important issue. As most well-established joining techniques for metallic structures are not directly applicable to composites, and because thermoplastics are difficult to bond adhesively due to their chemical inertness, another way of making structural joints has been considered, called fusion bonding [1]. The fusion bonding process involves consecutively heating and melting the thermoplastic polymer of the composite surfaces to be joined and then pressing the parts together for consolidation. With the infrared welding process, infrared radiation is transmitted to the parts being heated. Absorption and conversion of electromagnetic radiation melts the thermoplastic material in the composite structure. The infrared welding cycle (Fig. 1) can be divided into three processing steps: i) heating the surface area of the component by infrared radiation, ii) change-over from the heating to the pressure setup, and iii) joining and cooling of the bond under pressure to allow the matrix to solidify.

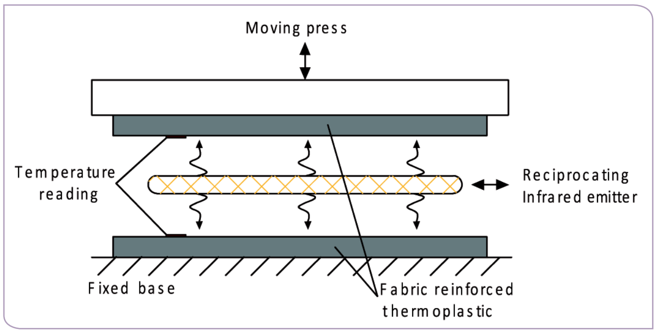

Fig. 1: Schematic of the infrared welding process

Critical processing parameters are the heating time, heating distance (distance between the heating source and the part), welding pressure and consolidation time.

Thermal diffusion into the parts can be a problem when reinforcement materials with high thermal conductivity are used, such as carbon fabrics. This heat dissipation results in limitations on temperature and heating time during the bonding process. When the heating source is applied for too long, a problem of deconsolidation and delamination between the laminae can occur. In addition, high temperatures may degrade the thermoplastic. Such thermal effects can be minimized by heating only the bond areas on the composite part, at an optimized temperature rate and profile.

Composite material

The material used is a carbon fabric reinforced polyphenylene sulphide (PPS) composite called Cetex®, which was supplied by the company Ten Cate – Aerospace Composites [2]. The fibre type used is the carbon fibre T300J 3K and the weave pattern is a 5-harness satin weave. The following stacking sequence was used for this study: $[(0^\circ, 90^\circ)]_{4s}$, where $(0^\circ, 90^\circ)$ represents one layer of fabric. The individual plates were produced by hot pressing at a temperature of 310°C and a pressure of 10 bar. The in-plane elastic properties and tensile strength properties of the Cetex® composite material are listed in Table 1.

Tab. 1: Elastic and strength properties of the Cetex® composite material

Mechanical property	Unit	Value
Tensile modulus warp E_{11}	[GPa]	56
Tensile modulus weft E_{22}	[GPa]	54
Poisson coefficient υ_{12}	[-]	0.033
In-plane shear modulus G_{12}	[GPa]	4.040
Tensile strength warp X_T	[MPa]	758
Ultimate strain warp ε_{11}^{ult}	[-]	0.011
Tensile strength weft Y_T	[MPa]	755
Ultimate strain weft ε_{22}^{ult}	[-]	0.013
In-plane shear strength S_T	[MPa]	119

Joint fabrication and strength assessment

One-sided welding

Preliminary tests have shown that joints made between the standard off-the-shelf plate specimens were of poor quality, since there was insufficient thermoplastic material present to form a joint [3]. As such, extra thermoplastic PPS material should be added to the bond area. In a first attempt, extra layers of pure PPS sheet material were added simply by laying the PPS sheets on the bottom component surface and allowing them to melt in the same melting phase as the specimens. This principle, referred to as 'one-sided welding', consists of 3 main processing steps which are shown in Figure 2.

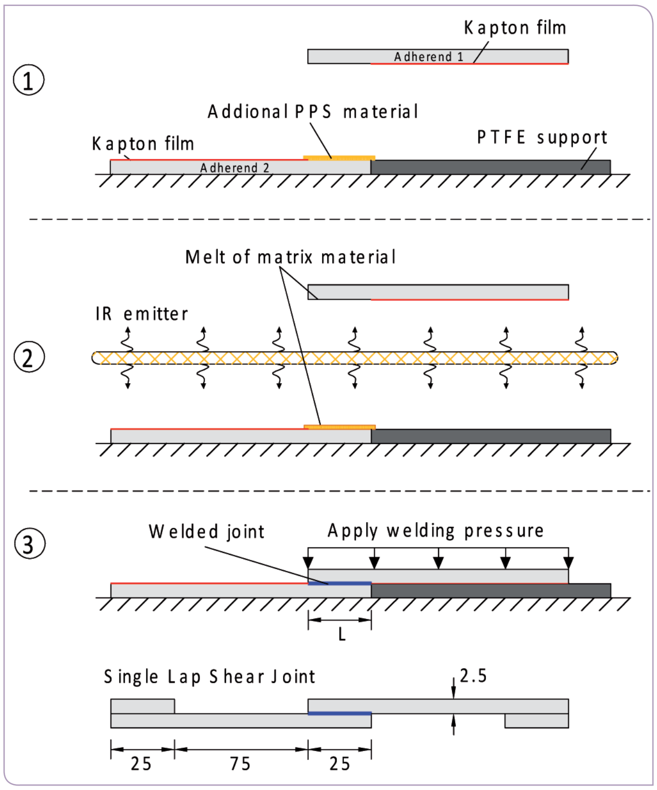

Fig. 2: Sequential processing steps for one-sided welding

In Step 1 of the bonding process, additional PPS material is placed at the location where the bond is needed. The remaining area of the specimen is shielded with heat-resistant film so that it does not reach the melting temperature. Next, the specimens are heated by infrared radiation until the PPS has melted (Step 2), which is determined by the temperature control unit. Step 3 consists in the cooling and reconsolidation of the matrix material at the joint. Here, it is important that the applied load be maintained until the resin has sufficient strength and stiffness to suppress delamination between the individual laminae.

Quasi-static experiments until failure are quite often used in order to assess the strength and reproducibility of the welds. At present, there is not yet a standardized method for testing welded joints, but various standards and test setups are available for examining the strength of adhesive bonds or the growth of delaminations [4, 5]. For evaluating the strength and the quality of the welds, the most commonly chosen experimental setup is the lap shear strength test (LSS), which is standardized in the ASTM D5868-01 standard.

Figure 3 gives an overview of different lap shear experiments for the one-sided welding procedure where the influence of consolidation pressure and number of PPS layers is considered. As can be seen in the figure, the reproducibility for welding cycles 8 (LS-8) and 9 (LS-9) is fairly non-existent. Not only is there significant variation between specimens from both cycles, but also the reproducibility is low within one cycle.

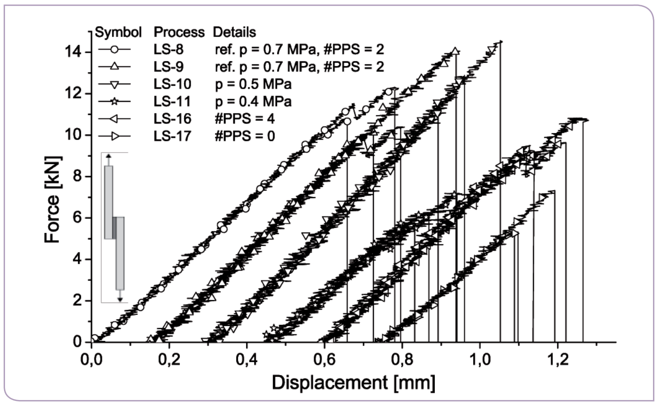

Fig. 3: Force-displacement response of the one-sided welding process

For cycles 10 and 11, the pressure during consolidation was lowered. This has a positive effect for cycle 10, resulting in higher strengths, but when the pressure becomes too low the strength also significantly decreases. Higher pressures were also attempted, but in general the main effect was that all liquid PPS was pushed out of the weld, resulting in poor strength. Pressures between 0.5 and 0.7 MPa seemed to be optimum values regarding this effect. For cycles 16 and 17, the number of PPS sheets placed inside the weld was varied. For test run LS-16, a lot more of the liquid PPS was pushed out of the weld compared to the other cycles, partially ruling out the effect of the extra layers and resulting in lower strength. More layers of PPS combined with a lower pressure to avoid the PPS "push-out" also resulted in lower strengths. Using no extra sheets of PPS has an even worse effect on the failure forces of the bond, as these are the lowest of all experiments discussed here. An optimum choice for this welding procedure appears to be two layers of PPS.

By the time the initial pressure was applied, the temperature had already dropped to around 240°C as a result of convective cooling to the ambient air. This, however, is an important temperature for PPS, as it is approximately the temperature where crystallization occurs during cooling. The cooling rate during the pressure step of the welding process has a great influence on the strength of the bond and can be examined with differential scanning calorimetry (DSC) [6,7,8]. If the temperature must be controlled more accurately, it is recommended that both plunger and anvil have a temperature-controlled heating and cooling system implemented.

Two-sided welding

The principle referred to as 'one-sided welding' worked but yielded poor quality and poor reproducibility of the bonds, which are not acceptable in any production process. Therefore, it was decided to add the PPS in a separate phase prior to welding, as illustrated in Figure 4.

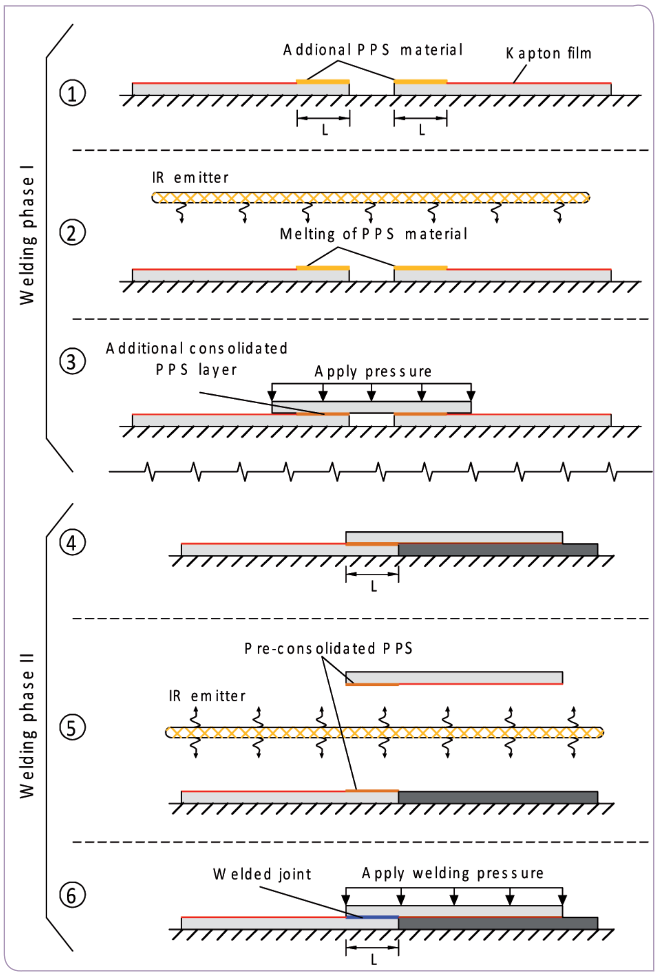

Fig. 4: Sequential processing steps for two-sided welding

In the initial preparation phase, referred to as Welding Phase I, layers of PPS are placed exactly at the location where the bond is expected (Step 1). The remaining area of the specimen is then shielded with a heat-resistant film, like in the previous welding setup. The specimens are heated until the melting temperature of the PPS material is reached (Step 2). In Step 3, the PPS is pushed on the surface with a polished aluminium plate, using just enough pressure to ensure a flat surface.

In the actual welding phase, referred to as Welding Phase II, the specimens are first placed according to the desired geometry (Step 4). A PTFE-coated support is used to ensure a correct positioning of the top adherend of the lap shear specimen. In Step 5, the top specimen is lifted with the plunger and the vacuum setup, and the temperature sensor is attached to the bottom sample. Both specimens are heated to the desired temperature and/or until enough PPS has melted. For Step 6, the infrared lights are removed and the plunger applies the necessary consolidation pressure. During the melting phase, the heat-resistant film still functions as a shield to prevent melting of this area. The paragraph above describes the two-sided welding process, since PPS is pre-consolidated on both adherends prior to welding. If no pressure is applied with the aluminium stamp in Step 3, the PPS forms air pockets and a very rough surface, making accurate positioning for the welding phase impossible. The main purpose of welding phase I is to have extra layers of PPS attached to the surface of the adherends. This step could also be implemented in the production process of the Cetex® composite laminates to ensure a PPS-rich area on the surfaces of the plates.

Figure 5 shows the results of the lap shear experiments, again with a horizontal offset between the cycles for clarity.

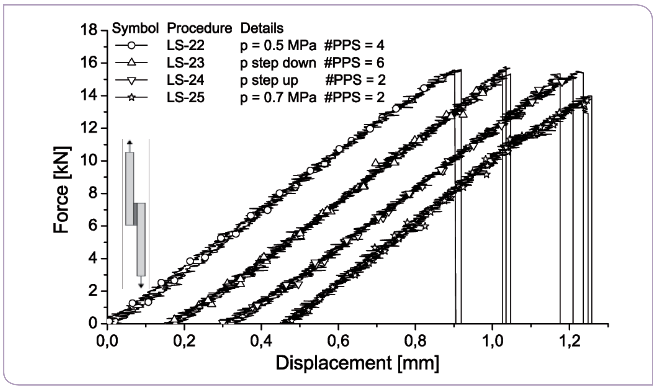

Fig. 5: Force-displacement response of the two-sided welding process

Two remarks can be made: 1) the reproducibility within a single welding cycle is very high, especially when compared to the results from one-sided welding, and 2) even between batches with different settings, which in some cases had a significant influence for the one-sided welding procedure, the reproducibility is still remarkable. As such, a fairly large process window is available to produce qualitative results. However, the last welding cycle, LS-25, shows that there are limits on the process window, as the strength of this cycle is lower than the others. Apparently, the combination of only two layers of PPS with a consolidation pressure of 0.7 MPa leaves insufficient PPS in the bond to achieve a high strength.

The fracture surfaces of some specimens were examined with scanning electron microscopy to try to determine a reason for the difference in failure strength and scatter between both welding processes. Figure 6 shows a few examples where the main difference can be clearly distinguished. For the one-sided welding process (Figure 6 (a)), cavities of various sizes such as those illustrated were always present on the surface, but they were not evenly distributed over the entire surface, possibly causing the larger scatter on the results. Such cavities were never found in the two-sided welding procedure, the entire fracture surfaces being similar to the images shown in Figure 6(b).

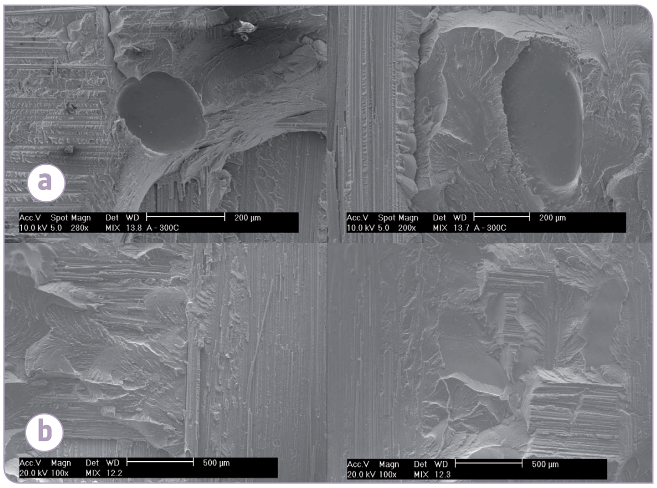

Fig. 6: SEM observation of the fracture surfaces (a) One-sided welding, cavities present (b) Two-sided welding, no cavities present.

The research on infrared welded joints has already revealed interesting results, so the study on the properties of these bonds is being continued. The dynamic fatigue behaviour of infrared-welded joints is currently being investigated, as it plays an important role in reliability-based design of parts and structures.

Conclusions

Infrared welding is a fast, economical and safe method for joining plastics. It can be easily automated and processing conditions can be easily monitored. Because it is a non-contact heating method, it can be used for continuous joining. It was found that although high failure loads are possible, the one-sided welding method yields very irreproducible results, not only between separate welding cycles with the same settings, but also between the three specimens coming from one cycle, which of course cannot be allowed. Two-sided welding showed very reproducible results, both within a single welding cycle and when comparing different welding cycles. Furthermore, there seems to be little influence, within certain boundaries, of the amount of PPS added and the consolidation pressure, yielding a wider process window. The latter is interesting, of course, if this technique is to be implemented in a production environment.

Infrared welding can be used to form joints between large and complex parts and can be made fully automated, resulting in fast and economical production runs. High reproducibility and quality of the welded bonds can be obtained at high welding temperatures that can be reached with infrared emitters, allowing welding of virtually all thermoplastic materials. ■

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